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THE EFFECTS OF FUEL AND CYLINDER GAS DENSITIES ON THE CHARACTERISTICS OF FUEL SPRAYS FOR OIL ENGINES

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SUMMARY

This investigation was conducted at the Langley Memorial Aeronautical Laboratory as a part of a general research on fuel-injection engines for aircraft. The purpose of the investigation was to determine the effects of fuel and cylinder gas densities upon several characteristics of fuel sprays for oil engines.

The start, growth, and cut-off of single fuel sprays produced by automatic injection valves were recorded on photographic film by means of special high-speed motion-picture apparatus. This equipment, which has been described in previous reports, is capable of taking twenty-five consecutive pictures of the moving spray at the rate of 4,000 per second.

The penetrations of the fuel sprays increased and the cone angles and relative distributions decreased with increase in the specific gravity of the fuel. The density of the gas into which the fuel sprays were injected controlled their penetration. This was the only characteristic of the chamber gas that had a measurable effect upon the fuel sprays. Application of fuel-spray penetration data to the case of an engine, in which the pressure is rising during injection, indicated that fuel sprays may penetrate considerably farther than when injected into a gas at a density equal to that of the gas in an engine cylinder at top center.

INTRODUCTION

The fuels used by internal-combustion engines operating on the Otto cycle are practically limited thus far to the lighter and more volatile liquid hydrocarbons such as gasoline and kerosene. An outstanding advantage inherent in Diesel engines is that they may be operated on a wide variety of fuel oils. These oils range from those as light as kerosene to some so heavy that they are usually heated for delivery to the engine. In general the light distillates give somewhat better engine performance, but these fuels are more expensive.

The facility with which fuel oils may be atomized depends upon their physical characteristics, important among which are viscosity and specific gravity. Kuehn (Reference 1) gives information concerning the relative size of oil drops produced with kerosene, specific gravity 0.813, and gas oil, specific gravity 0.852. Somewhat smaller drops were obtained with kerosene, as might be expected. The effects of the physical characteristics of the fuel upon the penetration, general shape, and distribution of fuel sprays injected into the dense gases in an engine are important considerations in the successful operation of the engine. Some knowledge of these physical effects on oil sprays should lead to a more successful use of various grades of fuels in all classes of oil engines.

The question has been raised at various times whether it is the pressure or the density of the gases in the cylinder which controls oil-spray penetration and distribution in an engine. Investigation of these effects is important because injection of the fuel generally starts several degrees before top center, when the pressure in the cylinder is only 200 or 300 pounds per square inch, and usually continues up to and beyond top center, when the pressure due to compression may range from 350 to around 550 pounds per square inch, depending upon the engine design. After combustion starts the pressure may rise considerably higher. (References 2 and 3.) The density of the gases during compression and combustion, however, varies only with the position of the piston and compression ratio. Thus while the cylinder gas pressures may increase several hundred per cent during injection of the fuel, the gas densities will usually vary less than 100 per cent.

The viscosity of the chamber gas may also affect oil spray characteristics. The viscosities of the gases in an engine cylinder are higher during injection of the fuel because of the high temperatures caused by the compression of gases. According to the kinetic theory of gases the viscosity of a gas increases in proportion to the square root of the absolute temperature. Actually the viscosity of a gas increases somewhat faster than this. (References 4 and 5.) An investigation of the effect of gas density and viscosity on spray characteristics is important, therefore, in order to provide data for the better application to engine conditions of results from researches on fuel sprays injected into gases at room temperature.

The object of this investigation, conducted at the Langley Memorial Aeronautical Laboratory at Langley Field, Va., was to determine the effects of some of the physical characteristics of the fuel, and the density and viscosity of the spray chamber gas, upon the penetration, general shape, and distribution of fuel sprays for various injection conditions.

Two injection valve assemblies were used in each test. One valve produced a noncentrifugal spray and the other a high-centrifugal spray. Tests were made with four different fuels having specific gravities ranging from 0.70 to 0.90. Each fuel was injected at 8,000 pounds per square inch pressure into a spray chamber containing nitrogen gas at atmospheric, 200, 400, or 600 pounds per square inch pressure in the tests on fuel characteristics. Nitrogen, carbon dioxide, helium, or air were used at these pressures in the spray chamber to determine the effects of gas density. Tests were also made with these different gases at pressures calculated to give constant gas densities in the spray chamber to determine the effects of gas viscosity.

METHODS AND APPARATUS

The general method employed to study the effects of fuel characteristics and spray chamber gas density and viscosity on fuel sprays was to record on photographic film the start, development, and cut-off of single sprays from an automatic injection valve. This was accomplished by injecting each of the fuels investigated into a spray chamber containing one of the gases under pressure and taking successive pictures, at high speed, of the moving spray with the N. A. C. A. fuel-spray photography apparatus. This equipment (References 3 and 6) is capable of taking 25 consecutive, well-defined pictures of a fuel spray at a rate of 4,000 per second. By measuring the fuel spray images recorded on photographic film, data were obtained on the penetrations, spray-cone angles, volumes and relative distributions of the sprays produced from the four fuels studied and the effect of injection into the various gases.

A diaphragm type injection valve was used in this investigation. It was fitted with two different stem and nozzle assemblies, one of which had 90-degree or axial fuel grooves and the other 23-degree helical fuel grooves near the end of the valve stem. The former produced a noncentrifugal spray and the latter a high-centrifugal spray. This injection valve has been described in N. A. C. A. Report No. 268 (Reference 7).

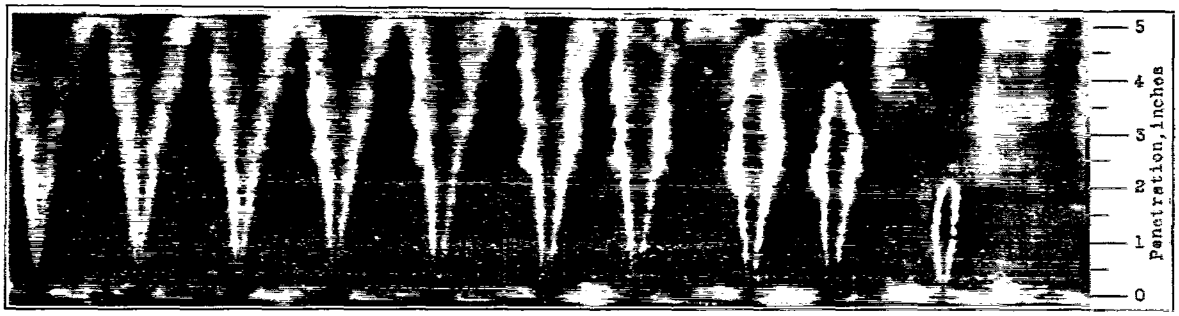
RESULTS AND DISCUSSION

Figure 1 shows two series of pictures, one of a noncentrifugal spray and the other of a high-centrifugal spray. Diesel oil was injected from the automatic injection valve at 8,000 pounds per square inch pressure into the spray chamber containing air at 200 pounds per square inch pressure for these tests. These photographs illustrate the kind of spray records obtained throughout this investigation, similar photographic records being taken for each fuel, and spray chamber pressure and gas studied.

FUEL DENSITY

Fuel spray penetrations for various time intervals during and following injection for both noncentrifugal and high-centifugal sprays similar to those shown in Figure 1 are presented in Figures 2 and 3. Diesel oil having a specific gravity of 0.85 at 80° F. was injected at 8,000 pounds per square inch into the spray chamber containing air at atmospheric, 200, 400 or 600 pounds per square inch pressure. These penetration-time curves are representative of the results obtained with the various fuels investigated. These and similar curves for the other fuels form the basis from which crossplotted data on the effects of specific gravity were derived.

Figure 4 shows the results obtained when the penetrations, spray-cone angles, and distributions of both noncentrifugal and high-centrifugal sprays are plotted against the specific gravity of the fuels studied. The data is for injection at 8,000 pounds per square inch, a spray chamber pressure of 200 pounds per square inch using nitrogen, and a time interval after the beginning of injection of 0.003 second. It may be noted that the penetration increased and the spray-cone angle decreased with increase in the specific gravity of the fuel injected. With the high-centrifugal injection valve, having 23° helical fuel grooves, the spray-cone angle was decreased 20 per cent and the pentration was increased 16 per cent for an increase in the specific gravity of the fuel from 0.80 to 0.90. These data indicate that the heavy fuel is more difficult to atomize, and that the greater inertia of the large spray particles of the heavy fuel results in greater penetration.



Injection pressure, 8,000 pounds per square inch. Noncentrifugal spray   Chamber pressure, 200 pounds per square inch. Diesel oil injected into air

Injection pressure, 8,000 pounds per square inch. High-centrifugal spray   Chamber pressure, 200 pounds per square inch. Diesel oil injected into air

FIG. 1.—Effect of centrifugal force on fuel sprays

The curves in this figure emphasize the large differences in penetration and spray-cone angle that may be obtained under the same injection conditions with non-centrifugal and high-centrifugal injection valves.

The increase in volume which a drop of fuel undergoes when it is discharged from an injection valve in the form of a spray is a measure of both the ability of the injection valve to distribute and atomize the fuel and the fuel's adaptability for spray formation. The distribution value of a fuel spray produced by any injection valve or injection condition is obtained by calculating the ratio of the spray volume to the volume of the fuel in the spray. The spray volume is approximately determined by summation of the volumes of a number of disks into which the photographic spray images may be divided for volume calculations. The volume of the oil in the spray is calculated from weight determinations of many sprays injected under the same test conditions and caught in a special container.

Figure 4 also shows the spray distribution values of the four fuels investigated for both the noncentrifugal and the high-centrifugal injection valve. The decrease in distribution and probably also in atomization with increase in specific gravity of the fuel for both types of injection valves are noteworthy, the heavy fuels being more difficult to distribute and atomize. The distribution values for the noncentrifugal injection valve range from 580 for gasoline to 460 for heavy fuel oil, a decrease in distribution of about 21 per cent. The distribution values for the high-centrifugal injection valve range from 1,080 for gasoline to 980 for heavy fuel oil, a decrease of only about 9 per cent. These data indicate the value of using centrifugal force to distribute and atomize heavy fuels.

GAS DENSITY AND VISCOSITY

The effect of injecting similar oil sprays into gases of different densities in the spray chamber is shown in Figure 5. Diesel oil was injected at 8,000 pounds per square inch pressure into helium, nitrogen, and carbon dioxide, each at a pressure of 200 pounds per square inch. All injection conditions were maintained constant. The difference in penetration obtained with these three gases at the same pressure definitely shows that the physical characteristics of the gases affect spray penetration.

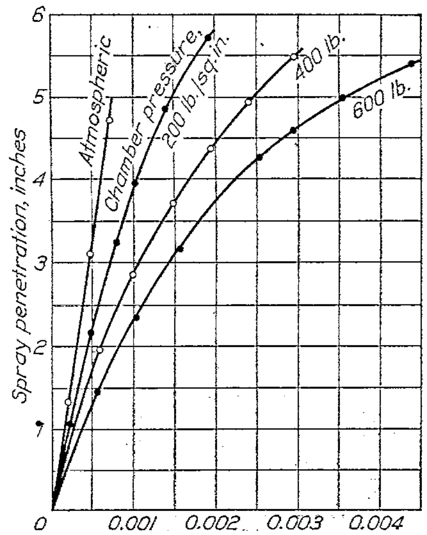


FIG. 2.—Effect of chamber pressure on spray penetration. Injection pressure, 8,000 pounds per square inch. Orifice diameter, 0.022 inch. Groove helix angle, 90°. Ratio of orifice length to orifice diameter, 2. Ratio of orifice area to groove area, 0.63

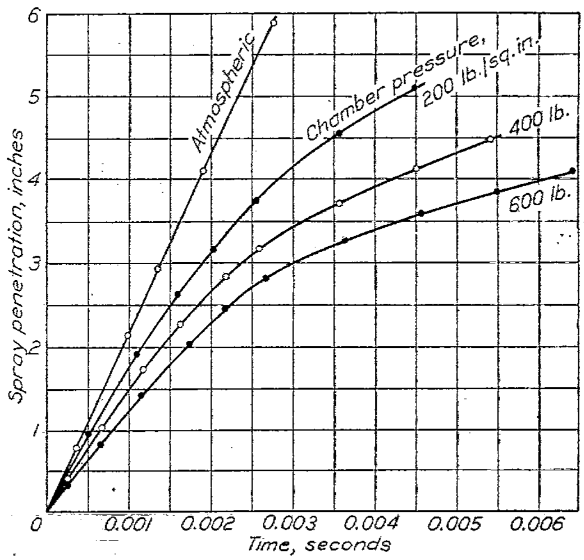


FIG. 3.—Effect of chamber pressure on spray penetration. Injection pressure, 8,000 pounds per square inch. Orifice diameter, 0.022 inch. Groove helix angle, 23°. Ratio of orifice area to groove area, 0.63. Ratio of orifice length to diameter, 2

Further tests were made using gas pressures in the spray chamber that were calculated to give the same density for each gas. The spray penetration was found to be the same for all gases under these conditions, thus showing that gas density rather than gas pressure controls spray penetration. The viscosities of the gases investigated vary from 148 to 202 (Reference 8), but this property of the gases produced no measurable effect upon either the appearance of these sprays or upon their penetration.

The effect of gas densities from 0.08 to 4.80 pounds per cubic foot upon spray penetration after 0.001, 0.002, and 0.003 second is shown in Figure 6. These curves were cross-plotted from results obtained by injecting similar Diesel oil sprays into the three different gases investigated at several different pressures. The abscissas give the gas density and the equivalent air pressure. Each point is labeled to show the gas used at that density. Since all the points lie on smooth curves, it may be again noted that the density and not the pressure or viscosity of the gas in the spray chamber controls spray penetration.

The effect of gas density on the spray tip velocity is shown in Figure 7. The rapid decrease in spray tip velocity with increase in gas densities up to about 1 pound per cubic foot is worthy of note, as this range covers the densities usually occurring in engine cylinders. The curves converge at zero density because the spray velocity will not diminish with time for injection into a vacuum except for the effects of vaporization.

The effect of spray chamber gas density upon the volume growth of centrifugal sprays, with time, is shown in Figure 8. The volume growth of these sprays is practically negligible for about 0.0005 second following the beginning of injection, after which it increases first at an accelerating rate and then, after about 0.0015 second, at practically a constant rate. These curves indicate that the spray is poorly distributed and probably little atomized during about the first 0.001 second. Under these conditions ignition of the fuel in an engine cylinder would probably be impossible in a time interval less than about 0.001 second after the beginning of injection because of the practically complete lack of atomization and, therefore, the prevention of vaporization by the highly heated cylinder air.

The data in Figure 8 show that large decreases in the volumes of similar sprays occur with increased gas densities. Since the density of the gas in an engine cylinder is proportional to the compression ratio, the volume growth of a fuel spray in an engine cylinder will depend upon the compression ratio. For the data given in Figure 8, the volume of these fuel sprays at various time intervals after the beginning of injection was found to vary as given in equations 1, 2, and 3.

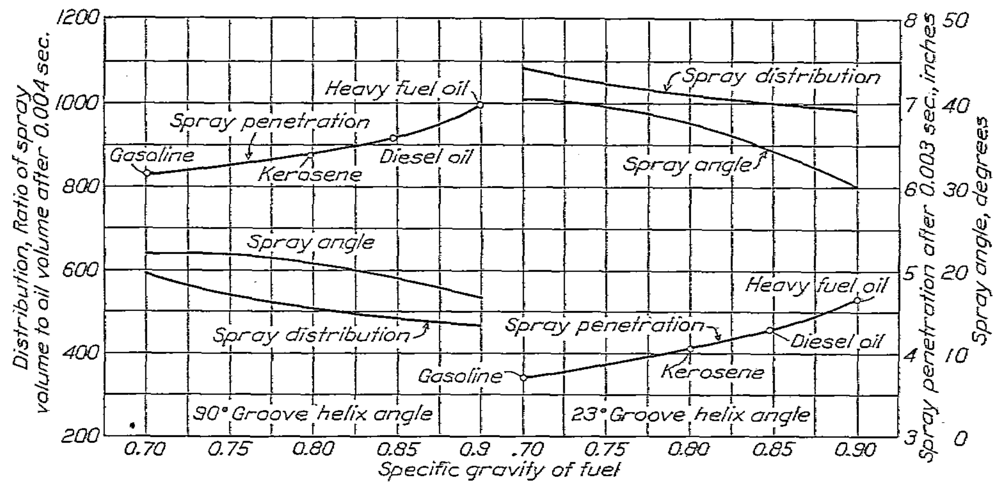


FIG. 4.—Effect of fuel on spray characteristics. Injection pressure, 8,000 pounds per square inch. Chamber pressure, 200 pounds per square inch. Orifice diameter, 0.022 inch. Ratio of orifice length to orifice diameter, 2. Ratio of orifice area to groove area, 0.63

(1) $V = 1.85 - 2.0 \log_{10} D.$ (Injection for 0.002 sec.)

(2) $V = 3.75 - 4.2 \log_{10} D.$ (Injection for 0.003 sec.)

(3) $V = 5.90 - 6.4 \log_{10} D.$ (Injection for 0.004 sec.)

V = Spray volume in cubic inches.

D = Density of spray chamber gas in pounds per cubic foot.

APPROXIMATE APPLICATION OF PENETRATION DATA TO ENGINE CONDITIONS

In the fuel spray investigations described thus far, the fuel sprays have been injected into a chamber containing gas at constant pressure. In actual engine operation, injection usually starts a short time before top center and therefore before maximum compression pressure has been reached, and continues while the compression pressure is rapidly increasing. In order to obtain approximately true spray penetration-time data, a composite curve has been drawn by cross-plotting from data obtained by injection into gases at various densities covering the range of cylinder gas densities occurring in an engine. Spray chamber gas pressures were used that were calculated to produce gas densities equal to those in an engine with a compression ratio of 10.3 for every 5° of crank travel after the start of injection. Injection of the fuel was assumed to start 30° before top center. Photographic records were taken of similar fuel sprays injected under each condition. The composite spray penetration curve, Curve I, in Figure 9, was obtained from these records. The second surve was obtained for a spray chamber gas density equal to that at engine top center. About 17 per cent greater spray penetration, after injection for 0.003 second, was obtained for injection into gases at densities varying as in an engine.

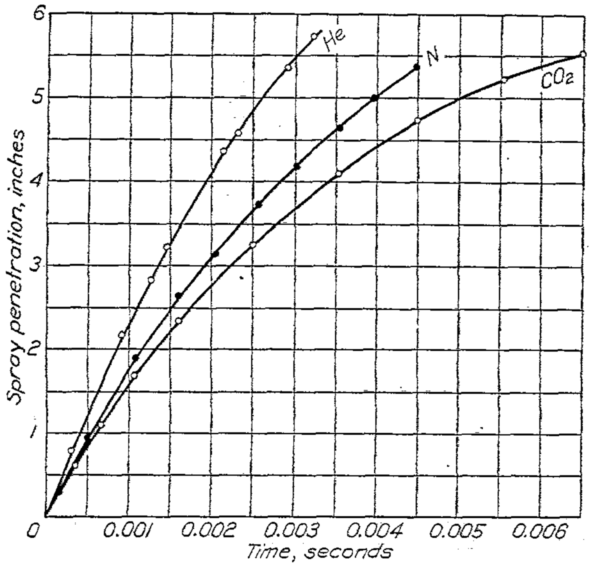


FIG. 5.—Effect of gas density on spray penetration. Injection pressure 8,000 pounds per square inch. Chamber pressure, 200 pounds per square inch. Orifice diameter, 0.022 inch. Groove helix angle, 23° Ratio of orifice length to orifice diameter, 2. Ratio of orifice area to groove area, 0.63

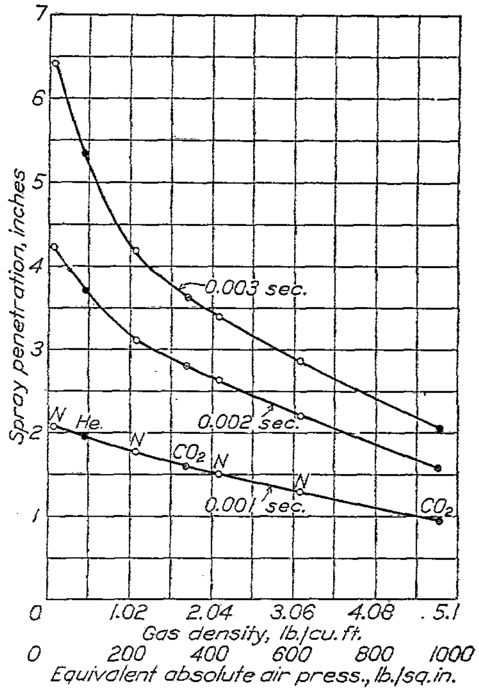


FIG. 6.—Effect of gas density on spray penetration. Injection pressure, 8,000 pounds per square inch. Orifice diameter, 0.022 inch. Groove helix angle, 23°. Ratio of orifice length to orifice diameter, 2. Ratio of orifice area to groove area, 0.63. Gas in spray chamber, nitrogen, carbon dioxide, or helium

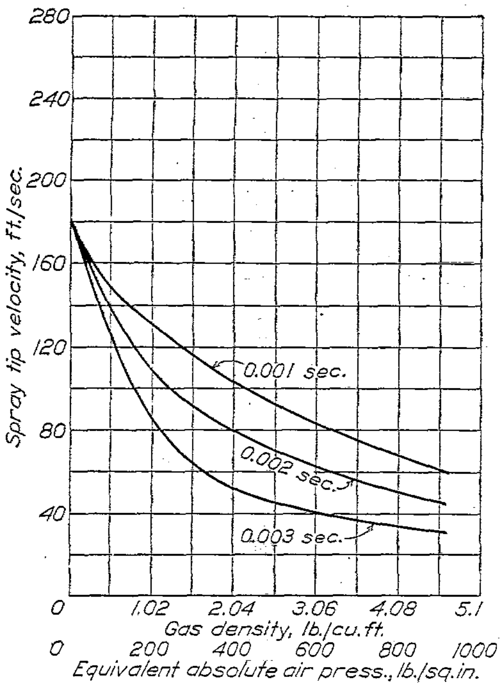


FIG. 7.—Effect of gas density on velocity of spray. Injection pressure, 8,000 pounds per square inch. Orifice diameter, 0.022 inch. Groove helix angle, 23°. Ratio of orifice length to orifice diameter, 2. Ratio of orifice area to groove area, 0.63

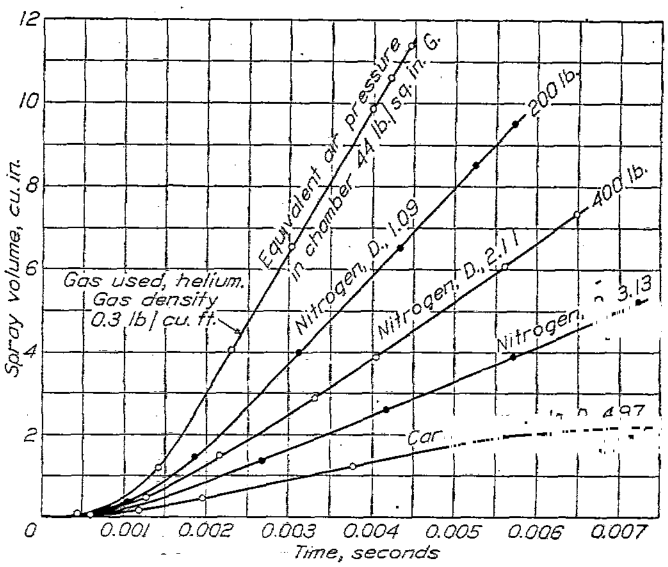


FIG. 8.—Effect of chamber pressure on the volumetric growth of centrifugal sprays. Injection pressure, 8,000 pounds per square inch. Orifice diameter. 0.022 inch. Groove helix angle, 23°

In the case of a fuel spray injected into an engine cylinder, gas temperature and turbulence would have appreciable effects on all spray characteristics. These effects remain to be determined.

CONCLUSIONS

The results of this investigation show that the spray penetration increases and the spray distribution, cone angle, and atomization decrease with increase in the specific gravity of the fuel oil. The effects of applying centrifugal force to fuel sprays is pronounced. The use of centrifugal force to atomize and distribute a fuel is more important for heavy fuels than for light fuels.

The density of the chamber gas was found to control spray penetration rather than the gas pressure. The kind of gas used in the spray chamber for conditions of constant density had no measureable effect on the fuel sprays. The effect of gas viscosity was, therefore, negligible.

A composite curve for spray penetration for injection into gases varying in density as in an engine, showed about 17 per cent greater penetration after 0.003 second than did the curve for a constant gas density equal to that at maximum compression.

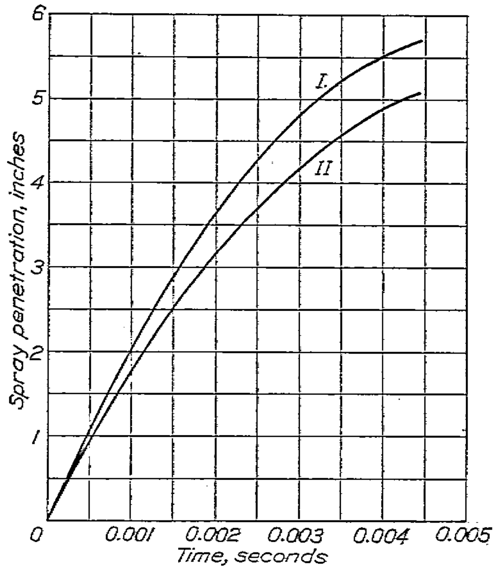


FIG. 9.—Approximate spray penetration in an engine cylinder
I. Approximate spray penetration in an engine cylinder: Compression ratio 10:3. Start of injection, 30° before top center.
II. Spray penetration in a gas at a density equal to that in an engine cylinder at top center. Injection pressure, 8,000 pounds per square inch. Orifice diameter, 0.022 inch. Groove helix angle, 23°

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
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